REPORT R-1815

INVESTIGATION OF THE EFFECTS OF RUBY LASER RADIATION ON OCULAR TISSUE

by

Jerry H. Jacobson
Harold W. Najac
Blossom Cooper

(New York Eye and Infirmary, N. Y. C.
Contract DA 36-038-AMC-685(A))

For

U. S. Army, Frankford Arsenal

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June 1966

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FIRE CONTROL ENGINEERING DIRECTORATE
FRANKFORD ARSENAL
Philadelphia, Pa. 19137

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ABSTRACT

A series of laboratory and field experiments on rabbits were conducte by the New York Eye and Ear Infirmary in order to establish tentative safe operational distances and conditions for use of the Frankford Arsenal XM23 Laser Range Finder. The measured far field corneal threshold dose for rabbits was tentatively determined to be 5×10^{-7} joule/cm^2. From this a possible human corneal threshold was calculated as 1.45×10^{-6} joule/cm^2. Based on this value, tentative safe operational distances were calculated as being 6460 meters for night (8mm pupil), 1615 meters for twilight (4mm pupil), and 914 meters for daylight (3mm pupil).

FOREWORD

This investigation was initiated by Andrew J. Britten of the Optical Laboratory, Fire Control Engineering Directorate, Frankford Arsenal, and was carried out by the Department of Electrophysiology of the New York Eye and Ear Infirmary.

Primary responsibility was assumed by Jerry Hart Jacobson, M.D., Director of the Research Department; Harold W. Najac, M.D. supervised and conducted the actual experimental exposures and evaluations, and Blossom Cooper, M.S., Physicist, was concerned with the physical equipment and problems of irradiance, dose and image size.

Animal experiments reported herein were conducted according to the "Principles of Laboratory Animal Care" established by the National Society for Medical Research.

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INTRODUCTION

The purpose of the study was to determine safe operational distances and conditions for the use of a specific instrument, namely, the Frankford Arsenal XM23 Laser Rangefinder, in the laboratory and in the field. The XM23 Rangefinder laser transmitter (receiver not used in these tests) consisted of a ruby laser oscillator with associated Q-switch components necessary to generate a monopulse output and a 7X telescope to narrow the output beam to 0.75 to 1.0 mil divergence. The last lens of the system measured 2" x 3/8". A sighting telescope was mounted on the instrument and collimated with the laser beam to aid in directing the beam into the rabbit's eye (see fig. 1). The laser was operated under the following conditions:

> Xenon Lamp, 1845 volts; trigger voltage 17.5 volts;
> Q-switch rotating prism, 17.5 volts

Voltmeters were used to monitor the lamp charging voltage and that of the rotating prism motor.

EXPERIMENTAL PROCEDURES

Preparation of Animals

Chinchilla grey rabbits weighing from 4.5 to 6.0 pounds were used. Animals were selected with finely dispersed, moderately dense pigment in the retina.

General anesthesia was obtained using pentobarbital sodium (25 mg/kg body weight). injected into the marginal ear vein (see fig. 2). Pupils were maximally dilated (approximately 8mm) with atropine (1%) and neo-synephrine (10%), and instilled in the conjunctival sac. Tetracaine (0.5%) was used to produce topical anesthesia. Retrobulbar injection of 1% procaine completed the anesthesia, and produced an exophthalmos desirable for the circumstances. This prevented the nystagmoid motion frequently observed with barbiturates. In addition, the lids were sutured behind the globe to further prevent motion. Corneas were kept moist with a solution of 5% glucose in .45% saline.

Figure 1. The XM23 Laser Transmitter Rangefinder at Fort Dix

Figure 2. Rabbit Being Anesthetized for Exposure

During exposures, animals were placed in a specially designed box which allowed the head to emerge from the front (see fig. 3). The head was tilted and maintained in such a position that the laser beam would fal on the retina below the optic nerve. This area was chosen because of the uniformity of the pigment distribution, the greatest accumulation of cones rendering this area more comparable to that of the human macula, and th approximation to the visual axis of the rabbit.

Laboratory Exposures

1. New York Eye and Ear Infirmary

At a distance of 17 cm from the telescope, a series of animals were exposed to the laser; two exposures with the unfiltered beam, and five with neutral density filters of 15%, 9% and 5% transmission. A lesio was produced by each exposure, however, the severity of the burn could not be ascertained ophthalmoscopically in each case because of the prese of vitreous hemorrhage obscuring the lesion. The eyes were then enuclea and evaluated with the aid of a magnifying lens. The lesion appeared oval with the long axis parallel to that of the laser beam. The retina and the choroid were destroyed in all cases; in one case the burn involved the sclera. The diameter of the burn varied from .9 to 1.4 mm.

2. Naval Applied Science Laboratory

Ten rabbits were exposed at a distance of 50 meters from the te scope. Energy levels down to approximately 26% of the total energy were obtained by means of neutral density filters. Two pupillary conditions, simulating day and night, were produced by use of mydriatic and myotic drugs administered topically.

An NML* .9427 gram blackened copper button calorimeter, wit an aperture of .1997 cm^2, was placed in close proximity to the rabbit's ey in order to sample an area of the laser beam as similar as possible to tha at the corneal plane. A Keithley milli-micro-voltmeter was used to detern the resultant potential. To increase the signal to noise ratio, the apertur was removed and the entire button area of 1.767 cm^2 was used. Thus, if

*Naval Materiel Laboratory, now known as Naval Applied Science Labora tory.

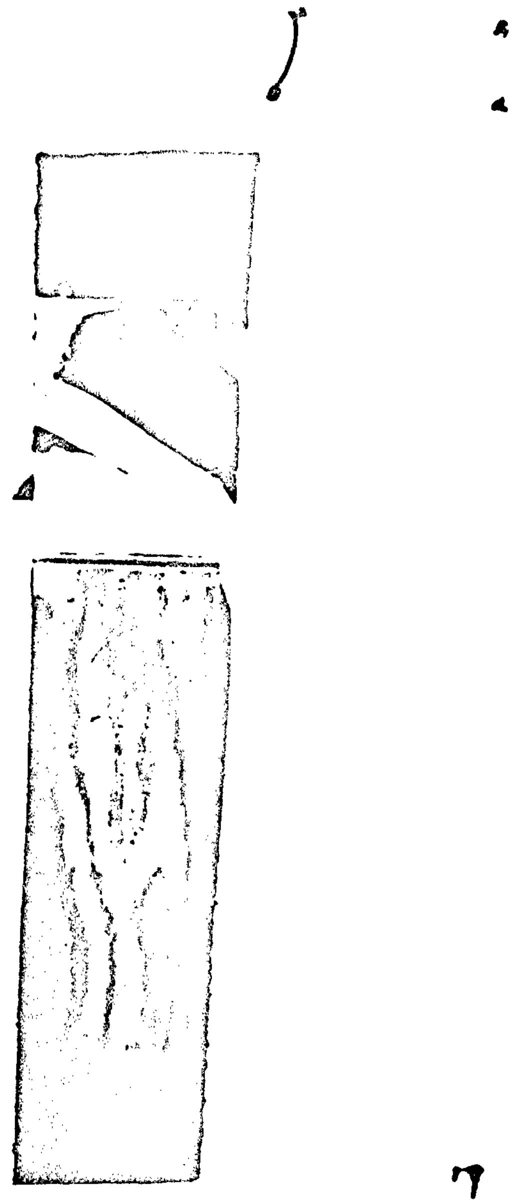

Figure 3. Rabbit in Box Ready for Exposure

$$k_a = 9.13 \text{ cal/cm}^2\text{/mv}$$

$$A_a = .1997 \text{ cm}^2$$

$$A_b = 1.767 \text{ cm}^2$$

the new sensitivity of the calorimeter without aperture is

$$k_b = \frac{9.13 \times .1997}{1.767} = 1.03 \text{ cal/cm}^2\text{/mv}$$

Stable voltage readings on the Keithley were obtained for only one energy level, that of no filtration in front of the laser. Other energy levels were calculated based on spectral transmission of the netural density filters as determined on a Beckman DK-2 Spectrometer at the laboratory.

Table I presents the data for intensity of lesion as a function of dose at 50 meters.

Range Exposures (Fort Dix)

Animals were placed in the beam of the laser under field conditions at ranges calculated, on the basis of the previous experimental laboratory studies, to be in the definitely pathological range, near visible threshold and below visible threshold.

Animals were examined immediately, 24 and 48 hours post-exposure. Some eyes were enucleated and examined for size and type of lesion.

Weather conditions were as follows:

Day	Time	Temperature	Humidity	Visibility
10/24/63	A. M.	74° F	80%	-
10/24/63	P. M.	45° F	91%	-
10/28/63	P. M.	54° F	82-98%	7 miles

Table I. INTENSITY OF LESION AS A FUNCTION OF DOSE AT 50 METERS

Pupil Diameter mm	Transmission of Filters %	Experimental Corneal Dose		Retinal Energy		Calculated Retinal Dose for .001 cm image*		Intensity Lesion
		cal/cm^2	$joules/cm^2$	calories	joules	cal/cm^2	$joules/cm^2$	
8	No filters	1.03×10^{-3}	4.3×10^{-3}	5.2×10^{-4}	2.2×10^{-3}	6.6×10^{2}	2.8×10^{3}	Dense mushroom vitreous hemorrhage, round area of retinal coagulation at site of hemorrhage.
8	57.5	5.9×10^{-4}	2.5×10^{-3}	3.0×10^{-4}	1.3×10^{-3}	3.8×10^{2}	1.6×10^{3}	Mushroom vitreous hemorrhage, round area of retinal coagulation, lesion smaller than previous one.
8	17.0	1.8×10^{-4}	7.3×10^{-4}	9.0×10^{-5}	3.7×10^{-4}	1.2×10^{2}	4.7×10^{2}	Vitreous hemorrhage; similar to abv but smaller
8	9.5	9.8×10^{-5}	4.1×10^{-4}	4.9×10^{-5}	2.1×10^{-4}	6.2×10	2.6×10^{2}	Vitreous hemorrhage in some cases and choroidal hemorrhage in others.
8	7.3	7.5×10^{-5}	3.1×10^{-4}	3.8×10^{-5}	1.6×10^{-4}	4.8×10	2.0×10^{2}	Similar to above, but smaller.

*Theoretical Image Size

Table I. (Cont'd)

Pupil Diameter mm	Transmission of Filters %	Experimental Corneal Dose		Retinal Energy		Calculated Retinal Dose for .001 cm image*		Intensity Lesion
		cal/cm^2	$joules/cm^2$	calories	joules	cal/cm^2	$joules/cm^2$	
8	2.8	2.9X 10^{-5}	1.2X 10^{-4}	1.5X 10^{-5}	6.0X 10^{-5}	1.9X 10	7.7X 10	No choroidal hemorrhage - central white area of coagulation poorly delineated, halo of edema, lesion is smaller than previous one.
8	2.5	2.6X 10^{-5}	1.1X 10^{-4}	1.3X 10^{-5}	5.5X 10^{-5}	1.7X 10	7.0X 10	No choroidal hemorrhage; central white area of coagulation, surrounded by pigmentary change and erythema.
8	1.9	2.0X 10^{-5}	8.4X 10^{-5}	1.0X 10^{-5}	4.2X 10^{-5}	1.3X 10	5.4X 10	Very small center of coagulation surrounded by concentric rings of pigmentary changes and erythema, diameter of center appeared smaller than choroidal vessel.
8	1.4	1.4X 10^{-5}	6.0X 10^{-5}	7.0X 10^{-6}	3.0X 10^{-5}	9.0	3.8X 10	Similar to above.

*Theoretical Image Size

Table I. (Cont'd)

Pupil Diameter mm	Transmission of Filters %	Experimental Corneal Dose		Retinal Energy		Calculated Retinal Dose for .001 cm image*		Intensity Lesion
		cal/cm^2	joules/cm^2	calories	joules	cal/cm^2	joules/cm^2	
8	.46	4.7X 10^{-6}	2.0X 10^{-5}	2.4X 10^{-6}	1.0X 10^{-5}	3.1	1.3X 10	Suspicious Area
8	.26	2.7X 10^{-6}	1.1X 10^{-5}	1.4X 10^{-6}	5.5X 10^{-6}	1.8	7.0	Suspicious Area
3	100	1.0X 10^{-3}	4.3X 10^{-3}	7.3X 10^{-5}	3.0X 10^{-4}	9.3X 10	3.8X 10^2	Choroidal hemorrhage not protruding into vitreous retinal coagulation, surrounded by dark pigmented border with accumulation of pigment in the center, possible vitreous burn.

*Theoretical Image Size

A calibrated RCA 917 vacuum phototube, in conjunction with a T ktronix 545 oscilloscope, was placed in close proximity to the rabbit's eye during exposure. Records of the potentials were obtained by means of a Polaroid camera mounted on the oscilloscope (see fig. 4).

Assuming far field conditions the area of the beam at the corneal plane is as follows:

D = diameter of circular area subtended on sphere of radius r

r = range

α = minimum dispersion angle of the beam
$= \sim .75$ mil
$= \sim 0.75 \times 10^{-3}$ radians

S = area of beam at range r

The solid angle Ω subtended by the laser beam is given by

$$\Omega = \frac{\frac{\pi D^2}{4}}{r^2}$$

$$= \pi/4\ (D/r)^2$$

$$= \pi/4\ (\alpha)^2$$

$$= 0.33 \times 10^{-6} \text{ steradians}$$

including a correction factor for the exit window lens and the area is

$$S = \Omega\, r^2$$

$$= 0.33 \times 10^{-6} \times r^2\, cm^2$$

considering the eye as a diffraction limited optical system the angular separation ξ of two distant points that can just be resolved cannot be less than ξ_F, the angular resolution determined by the Fraunhoffer diffraction

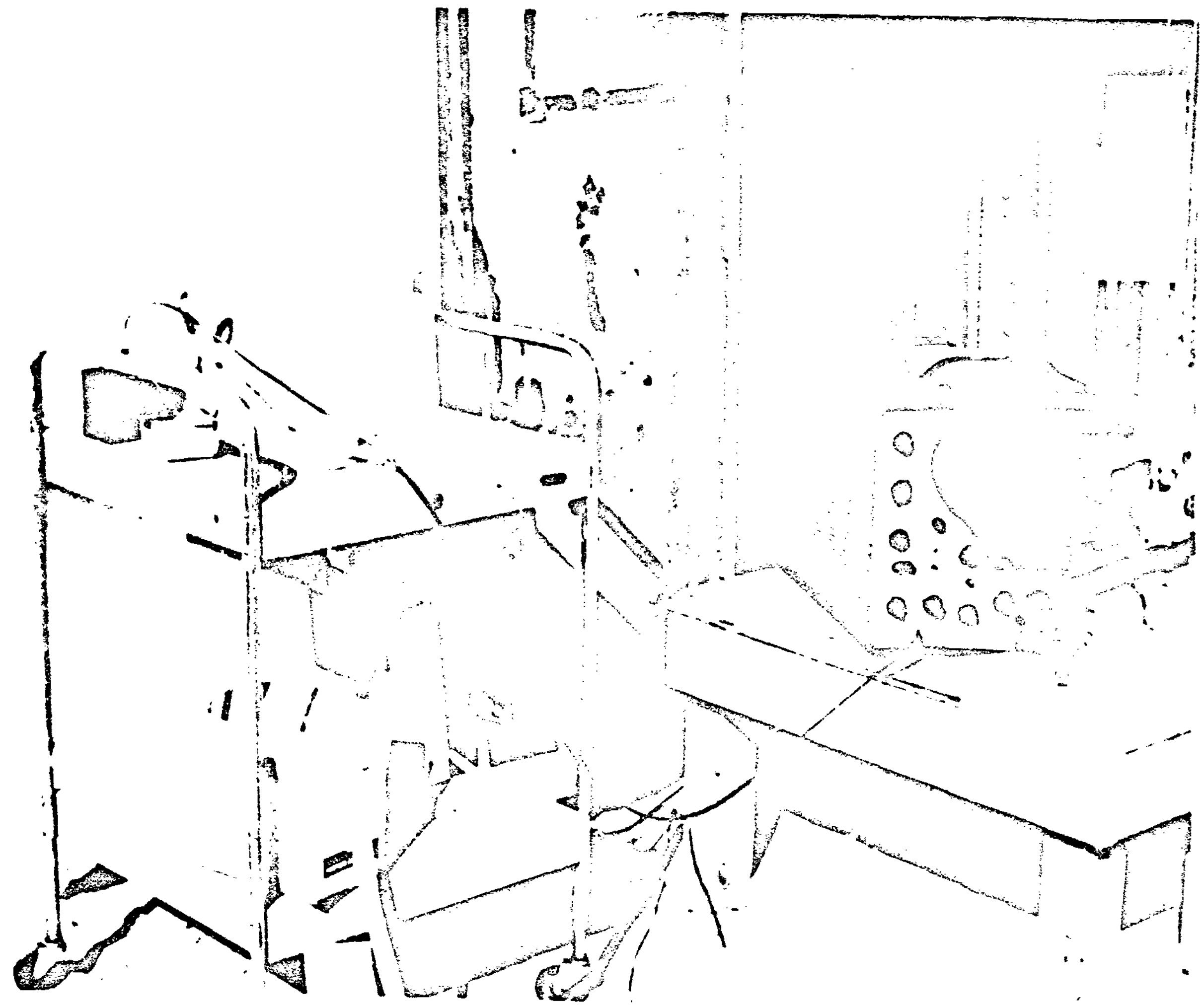

Figure 4. Calibrated RCA 917 Vacuum Phototube and Tektronix Oscilloscope

pattern produced by the pupil.[1] Using the Rayleigh criterion and for a circular pupil illuminated by a plane wave:

$$\xi \geq \xi_F = \frac{2.44\lambda}{D_E}$$

$$\xi_{\substack{\text{min.}\\ \text{night}}} = \frac{2.44\,(6.943 \times 10^{-5})}{.8} = .000212 \text{ rad.}$$

$$\xi_{\substack{\text{min.}\\ \text{day}}} = \frac{2.44\,(6.943 \times 10^{-5})}{13} = .000564 \text{ rad.}$$

where λ is the wavelength of the incident radiation and D_E is the diameter of the pupil the angle ξ_p is also the angle subtended by the Airy disk of the diffraction on image of a point produced by the pupil.

In a real eye, the retinal spot is larger than the Fraunhoffer spot. If f is the focal length of the rabbit's eye (equal to 1 cm), the minimum diameter h_{min} of any retinal image spot assuming exact focussing on the retina (no myopia or hypermetropy condition) is

$$h = (f_{min})\,(\xi_{min})$$

8 mm pupil: h night $= 1\,(.000213) \doteq .000212$ cm

4 mm pupil: h day $= 1\,(.000426) \doteq .000426$ cm

3 mm pupil: h day $= 1\,(.000569) = .000569$ cm

The sensititivy of the detector in volts/watt of incident energy was

$$j_p = j_o RT$$

[1]Solon, L. R. Aronson, Gould, G. Physiological Implications of Laser Beams, Science, 1961, Jul-Dec., Vol. 134.

where

j_o = .0028 amps/watt

T = transmission of filters used in front of phototube
N.D. 3.5; $1/T = 3.16 \times 10^3$
N.D. 2.5; $1/T = 3.16 \times 10^2$

R = resistance in the phototube circuit = 46.5 ohms

A_t = surface area of the detector = 3.03 cm^2

S_r = cross sectional area of laser beam at r

V = peak voltage of detector

therefore

$$1/A_t \times 1/j_t = k_t = 1/j_o R T A_t \text{ watt/cm}^2\text{/volt}$$

N.D. 3.5; k_t = 8010 watts/cm^2/volt
N.D. 2.5; k_t = 801 watts/cm^2/volt

The peak power in watts is thus

$$P = 8010 \times S_r \times V \quad \text{for N.D. 3.5}$$

and relative to a triangular pulse

$$E = 1/2\, k_t V_t t \text{ joules/cm}^2$$

where

E = energy density at corneal plane

t = duration of pulse

The first field range studied was 300 meters; however, dose determinations are not available for this distance.

The lesions observed at 300 meters appeared as a well delineated white area of coagulated retina with pigmentary changes in the center and periphery. In one lesion choroidal hemorrhage covered the entire area of the burn. Lesions were approximately .1-.45 mm in diameter as determined by direct measurement after enucleation six days after exposure. These lesions appeared smaller than the fresh lesions, with denser pigmentary border, atrophy of the retina and no edema.

Subsequently, animals were exposed at 400, 500 and 650 meters.

Lesions produced at 400 and 500 meters appeared well delineated with pigmentary changes at the periphery but no white coagulation. The center appeared thickened and less transparent than the surrounding retina.

The lesion produced at 650 meters was comparable to those produced at 400 and 500 meters but was poorly delineated.

One rabbit (both eyes) was exposed to the laser beam at 915 meters. No lesions were observed at this distance, under the particular meteorological conditions. Lack of time prevented further experimental verification of this possible "threshold condition." Table II presents the data for intensity of lesion as a function of dose in the far field.

SUMMARY OF DATA

The exposures that took place at 50 meters were considered to have taken place in the near field. Theoretically, (see footnote 1) the image angle is equal to the laser angle, and thus the image on the rabbit retina should be approximately .00075-.001 cm in diameter. The corneal dose for the minimal lesion known as a Suspicious area was 11.0×10^{-6} joules/cm^2.

The retinal image for a rabbit with an 8 mm pupil exposed in the far field was calculated from the Rayleigh formula as .000212 cm. No visible lesions were observed in 11 exposures for corneal densities of 7.0×10^{-6} joules/cm^2 and lower. A possible detector error of 30% due to misalignment gives a range of $7.0\text{-}10.0 \times 10^{-6}$ joules/cm^2 for the experimental

Table II. INTENSITY OF LESION AS A FUNCTION OF DOSE IN THE FAR FIELD

Pupil mm	Distance meters	Corneal Dose joules/cm^2	Retinal energy joules	Retinal Dose for .000212 cm image joules/cm^2	Intensity of Lesion
8	300	N O T	M E A S U R E D		Lesion
8	300				Lesion
8	300				Well delineated area with pigmentary change, larger than .5 mm
8	300				Rabbit died
8	300				Lesion
8	300				Suspicious lesion within 5 min.
8	300				Lesion
8	300				White center, surrounded by choroidal hemorrhage, large but less than .5 mm
8	300				Center pigmented, surrounded by red area, well delineated, edema, more intense than former but smaller in size
8	300				Lesion
8	400				Change in appearance of retina to a deeper red (erythema) boundaries well defined
8	400				Nothing immediately - Suspicious area observed three days later
8	400				Lesion immediately - Suspicious area observed three days later
8	400				Lesion observed three days later

Table II. (Cont'd)

Pupil mm	Distance meters	Corneal Dose joules/cm^2	Retinal Energy joules $\frac{(CD)\pi(.8)^2}{4}$	Retinal Dose for .000212 cm image joules/cm^2	cal/cm^2	Intensity of Lesion
8	400	14.0×10^{-6}	7.0×10^{-6}	2.0×10^{2}	4.8×10	Lesion
8	400	25.2×10^{-6}				
	Double	3.6×10^{-6}				
	Pulse	28.8×10^{-6}	14.4×10^{-6}	4.1×10^{2}	9.8×10	Lesion
8	400	9.8×10^{-6}				
	Multiple	1.0×10^{-6}				
	Pulse	$.5 \times 10^{-6}$				
		11.3×10^{-6}	5.7×10^{-6}	1.6×10^{2}	3.8×10	Suspicious, immediately becoming an erythemal lesion
8	400	14.0×10^{-6}	7.0×10^{-6}	2.0×10^{2}	4.8×10	Erythemal lesion
8	400	33.6×10^{-6}	16.8×10^{-6}	4.8×10^{2}	1.1×10^{2}	Suspicious area

Table II. (Cont'd)

Pupil mm	Distance meters	Experimental Corneal Dose joules/cm^2	Retinal Energy joules	Calculated Retinal Dose Assuming .000212 cm image joules/cm^2	cal/cm^2	Intensity of Lesion
8	500 Double Pulse	20.4×10^{-6} 4.8×10^{-6} 25.2×10^{-6}	12.6×10^{-6}	3.6×10^2	8.6×10	Suspicious area becoming a lesion within 10 minutes
8	500	17.0×10^{-6}	8.5×10^{-6}	2.4×10^2	5.7×10	Suspicious area
8	500	24.0×10^{-6}	12.0×10^{-6}	3.4×10^2	8.1×10	Lesion
8	500	22.0×10^{-6}	11.0×10^{-6}	3.1×10^2	7.4×10	Cornea cloudy - suspicious
8	650 Double Pulse	6.7×10^{-6} $.2 \times 10^{-6}$ 6.9×10^{-6}	3.5×10^{-6}	1.0×10^2	2.6×10	Lesion
8	650	---				Lesion - within three minutes
8	650	10.1×10^{-6}	5.1×10^{-6}	1.4×10^2	3.3×10	Lesion
8	650	5.1×10^{-6}	2.6×10^{-6}	7.4×10	1.8×10	Lesion

Table II. (Cont'd)

Pupil mm	Distance meters	Experimental Corneal Dose joules/cm^2	Retinal Energy joules	Calculated Retinal Dose Assuming .000212 cm image joules/cm^2	cal/cm^2	Intensity of Lesion
8	650	6.0×10^{-6}	3.0×10^{-6}	8.5×10	2.0×10	Lesion
8	915	6.0×10^{-6}	3.0×10^{-6}	8.5×10	2.0×10	Lesion
8	915	5.8×10^{-6}	2.9×10^{-6}	8.2×10	2.0×10	Lesion
8	915	4.0×10^{-6}	2.0×10^{-6}	5.7×10	1.4×10	Lesion
8	915	3.8×10^{-6}	1.9×10^{-6}	5.4×10	1.3×10	Lesion
8	915	5.8×10^{-6}	2.9×10^{-6}	8.2×10	2.0×10	Lesion
8	915	1.9×10^{-6}	1.0×10^{-6}	2.8×10	6.7×10	Lesion
8	915	4.8×10^{-6}	2.4×10^{-6}	6.2×10	1.5×10	Lesion
8	915	7.5×10^{-6}	3.8×10^{-6}	9.9×10	2.4×10	Lesion

value. Due to the very small sampling of experimental animals and the fact that the criterion for damage was that of a visible lesion, it is advisable to consider the visible threshold as less than 1×10^{-6} joules/cm^2 for the rabbit eye.

However, since visible observation of these minuscule retinal lesions is very difficult, the corneal dose in the far field might have to be reduced to 5×10^{-7} joules/cm^2 for the rabbit's eye. Table III presents calculated retinal energy densities (assuming 100% ocular transmission) as a function of image diameter.

The retinal doses were calculated to give some order of magnitude but it should be remembered that the retinal image diameter is based on theoretical considerations and proves to be the weakest link in pinpointing significantly usable numbers.

The other weak link is that of extrapolating from rabbit to man. Correction in the rabbit data can be made for the different focal lengths of the optical system, but macular structure, choroidal structure and pigmentation are the obvious differences that still must be accounted for.

It must be emphasized at this point that the report covers four months of project time and less of actual experimental work with a minimum number (24) of rabbits, and the criteria of no visible lesion.

Although more data are essential, some evidence has been gathered as to the energy associated with minimal retinal changes and thus tentative safe operation distances have been calculated.

TENTATIVE SAFE OPERATIONAL DISTANCES

1. Night Condition - 8 mm Pupil

If we assume the corneal threshold dose for the rabbit in the far field is

$$5 \times 10^{-7} \text{ joules/cm}^2$$

Table III. CALCULATED RETINAL DOSE AS A FUNCTION OF IMAGE DIAMETER

Pupil mm	Distance meters	Retinal Image* cm	Experimental Corneal Dose joules/cm^2	Experimental Corneal Dose cal/cm^2	Retinal Energy joules	Retinal Energy cal.	Calculated Retinal Dose joules/cm^2	Calculated Retinal Dose cal/cm^2
SUSPICION AREA - NEAR FIELD CONDITION								
8	50	.01	11×10^{-6}	2.7×10^{-6}	5.5×10^{-6}	1.4×10^{-6}	.07	.002
8	50	.005	11×10^{-6}	2.7×10^{-6}	5.5×10^{-6}	1.4×10^{-6}	.28	.07
8	50	.001	11×10^{-6}	2.7×10^{-6}	5.5×10^{-6}	1.4×10^{-6}	7.0	1.7
8	50	.00075	11×10^{-6}	2.7×10^{-6}	5.5×10^{-6}	1.4×10^{-6}	12.5	3.2
8	50	.0003	11×10^{-6}	2.7×10^{-6}	5.5×10^{-6}	1.4×10^{-6}	79.5	19.0
NO LESION - FAR FIELD CONDITION								
8	915	.000212	1.0×10^{-6}	2.4×10^{-7}	5×10^{-7}	1.2×10^{-7}	14.2	3.4
8	915	.000212	5.0×10^{-7}	1.2×10^{-7}	2.5×10^{-7}	6.0×10^{-8}	7.1	1.7
8	915	.001	5.0×10^{-7}	1.2×10^{-7}	2.5×10^{-7}	6.0×10^{-8}	.32	.08
8	915	.01	5.0×10^{-7}	1.2×10^{-7}	2.5×10^{-7}	6.0×10^{-8}	.003	.0007

*Retinal image diameters have been selected to illustrate the variability when specifying retinal dose.

and assuming the image on the human retina from the Rayleigh condition to be 1.7 times that of the rabbit retinal image diameter, the possible threshold corneal dose for the human is 1.45×10^{-6} joules/cm^2 (assuming 100% ocular transmission).

For a .2 joule laser, assuming 100% atmospheric transmission, the corneal dose = .2 joule/S cm^2, where S is the area of the laser beam at the plane of the cornea.

If

$$S = .2 \text{ joules}/1.45 \times 10^{-6} \text{ joules/cm}^2$$

$$= 1.38 \times 10^5 \text{ cm}^2$$

and

$$S = .33 \times 10^{-6} \times r^2 \text{ cm}^2$$

therefore

$$1.38 \times 10^5 = (1.33) \times 10^{-6} r^2$$

$$r^2 = 1.38/.33 \times 10^{11} = 41.8 \times 10^{10} \text{ cm}^2$$

and

$$r = 6460 \text{ meters}$$

2. Twilight Condition - 4 mm Pupil

The Rayleigh condition for the image on the human retina for a 4 mm pupil compared to that for an 8 mm pupil is $(8/4)^2$ larger in area and the total retinal energy is $(8/4)^2$ smaller.

The corneal threshold dose for a human with a 4 mm pupil is thus

$$\text{Corneal dose} = 16 \times 1.45 \times 10^{-6}$$

$$= 2.32 \times 10^{-5} \text{ joules/cm}^2$$

therefore, for a .2 joule laser

$$S = .2/2.32 \times 10^{-5} = 8.62 \times 10^{3}\ cm^{2}$$

$$S = .33 \times 10^{-6} \times r^{2} = 8.62 \times 10^{3}$$

$$r^{2} = 8.62/.33 \times 10^{9}\ cm^{2}$$

$$r^{2} = 26.1 \times 10^{9}\ cm^{2}$$

$$r = 1615 \text{ meters}$$

3. Day Condition - 3 mm Pupil

The Rayleigh condition for the image on the human retina for a 3 mn pupil compared to that for an 8 mm pupil is $(8/3)^2$ larger in area and the total retinal energy is $(8/3)^2$ smaller. The corneal threshold dose for a human with a 3 mm pupil is thus

$$\text{Corneal dose} = 50.3 \times 1.45 \times 10^{-6}$$

$$= 7.3 \times 10^{-5}\ \text{joules/cm}^{2}$$

therefore, for a .2 joule laser

$$S = .2 \text{ joules}/7.3 \times 10^{-5}\ \text{joules/cm}^{2}$$

$$= 2.74 \times 10^{3}\ cm^{2}$$

$$S = .33 \times 10^{-6} \times r^{2} = 2.74 \times 10^{3}$$

$$r^{2} = 2.74/.33 \times 10^{9}\ cm^{2}$$

$$r^{2} = 8.3 \times 10^{9}\ cm^{2}$$

and

$$r = 914 \text{ meters}$$

If no consideration is given to the concept of a change in the diffraction pattern size with change of pupil aperture, then for a 3 mm pupil aperture the corneal dose should be 1.03×10^{-5} joules/cm^2

$$S = .2 \text{ joules}/1.03 \times 10^{-5} \text{ joules/cm}^2$$

$$= 1.94 \times 10^4 \text{ cm}^2$$

$$S = .33 \times 10^{-6} \times r^2 = 1.94 \times 10^4$$

$$r^2 = 1.94/.33 \times 10^{10}$$

$$r^2 = 5.89 \times 10^{10} \text{ cm}^2$$

$$r = 2430 \text{ meters}$$

RECOMMENDATIONS

Based on this experimental study and for maximum safety, it is recommended that the operational conditions and distances specified by Frankford Arsenal be complied with until further studies indicate otherwise, i.e.,

8 mm pupil (night)	6550 meters
3 mm pupil (day)	2720 meters

1. Examination of Personnel

In addition to the animal studies described herein, six members of the Fire Control Engineering Directorate at Frankford Arsenal were examined in November 1963 to determine the presence of any lesions which might be ascribed to exposure in the course of work with the laser. Nine additional personnel of this Directorate were examined in January 1964. Five of these also demonstrated possible lesions but because of extremely small size the extent of scotoma could not be measured. Although none of these people looked directly into the beam of the laser two of them were, in fact, found to have small whitish areas similar to those to be expected from retinal laser burns situated in the paramacular area. Both of these individuals did state that there were occasions in which they might have been exposed to the laser beam by specular reflection from the surface of other equipment in the pathway of the beam.

These two individuals have scotomata (blind spots) which correspond to the areas described.

Both of these individuals had, in the past, also been in the vicinity of nuclear explosions and there is a possibility that the lesions observed were due to nuclear effects.

The symmetry of the lesions in these individuals, as well as the character of the lesions themselves, however, are more indicative of damage due to the laser. It must be presumed that these lesions were, in fact, laser induced.

2. Discussion

In view of the fact that the lesion produced by the laser could damage the retina without appreciable visual loss (small burn in paramacular area) it would be of value to establish a detailed funduscopic record for all personnel associated with a laser. In this manner, any lesion in the periphery or paramacular area occurring as a result of an exposure to the laser beam will be detected upon subsequent routine examinations.

... it is anticipated that the patient will sustain an immediate visual loss whose magnitude will depend upon the severity and the size of the lesion.

The absorption characteristics of the retina and choroid are such that for the 6943 Å ruby energy, approximately equal energy absorption takes place in each system. Rupture of the vessels of the choroid occur readily and vitreous hemorrhage are produced much more frequently with this monochromatic energy than with equal energy comprising the entire visible spectrum.

If massive vitreous hemorrhage occurs, complete visual loss will also occur immediately. Some absorption may occur of such hemmorrhage, with consequent improvement in vision.

One point of interest was apparent in one individual examined. By measurement of the size of the visually observable lesion in the fundus, as seen photographically (fig. A-1), the area of scotoma should have been approximately 0.6 cm in diameter, at one meter. Actually, the scotoma is larger, measuring about 2 cm in diameter as measured at one meter from the eye. This may indicate that the area of retinal tissue, which will not function following such a burn, is considerably larger than the area of the visible burn.

In this instance the visible retinal burn measured approximately 0.1 mm, while the area of retinal disfunction is apparently 0.3 mm.

This may also mean that the visible burn, as used in this study as a criterion for retinal damage, although of interest from a relative point of view, cannot be relied upon to provide a picture of retinal functional damage, thereby making the estimate of safe distance as obtained by this technique invalid. Because of this factor, it is suggested that additional animal studies, especially with primate eyes, which more closely approximate human anatomy, be conducted.

The initial examination of personnel associated with the laser should involve:

(1) Visual acuity

(2) Determination of refractive error if any

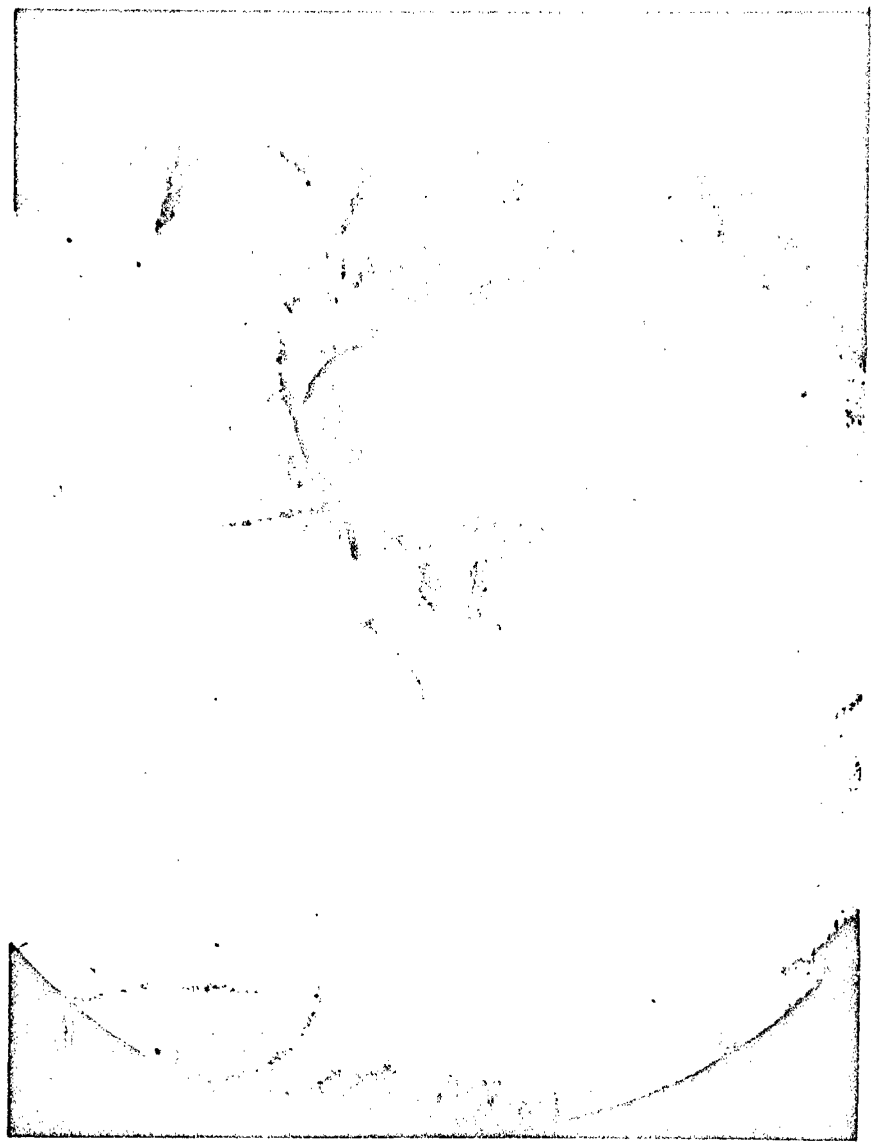

Figure A-1. Human Funduscopic Photograph

(3) Fundus examination and photography

(4) Visual field, central and peripheral, qualitative and quantitative, by tangent screen, Amsler chart and campimetry

(5) Color vision and depth perception

(6) Adaptometry

(7) Intraocular tension

followed by periodic examinations of a similar nature.

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13 ABSTRACT

A series of laboratory and field experiments on rabbits were conducted by the New York Eye and Ear Infirmary in order to establish tentative safe operational distances and conditions for use of the Frankford Arsenal XM23 Laser Rangefinder. The measured far field corneal threshold dose for rabbits was tentatively determined to be 5×10^{-7} joule/cm^2. From this a possible human corneal threshold was calculated as 1.45×10^{-6} joule/cm^2. Based on this value, tentative safe operational distances were calculated as being 6460 meters for night (8 mm pupil), 1615 meters for twilight (4 mm pupil), and 914 meters for daylight (3 mm pupil).

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